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SIMTAX

A Taxonomy for Warfare Simulation

Workshop Report
(14 -16 October 1986)
(9 - 10 December 1986)
(10 - 11 February 1987)

October 27, 1989

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This Military Operations Research Society workshop report faithfully summarizes the findings of a series of three short meetings of experts, users, and parties interested in the subject area. While it is not generally intended to be a comprehensive treatise on the subject, it does reflect the major concerns, insights, thoughts, and directions of the participants at the time of the meetings.

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I. BACKGROUND

The Department of Defense needs a wargaming and warfare simulation descriptive framework to guide the development, acquisition and use of models of warfare. The essential first step in producing such a descriptive framework is developing a wargaming and warfare simulation taxonomy or classification system.

A wargaming taxonomy would do more, however, than undergird a framework, a classification system would form an indispensable foundation for building a practical catalogue of conflict models and simulations. In the past, the lack of a useful taxonomy for classifying models has reduced the utility of such documents as the Joint Analysis Directorate's¹ "Catalog of Wargaming and Military Simulation Models." The only defined classification (really categorization) system used in this extensive volume is an alphabetical listing by model name. An accepted taxonomy, however, could lead to a catalogue that classified (and thus indexed and cross-indexed) its numerous models by how they were used, what they addressed, and how they were constructed.

Recognizing the basic need for constructing a taxonomy, the Military Operations Research Society sponsored a workshop series, all hosted by the SYSCON Corporation and all led by Mr Vincent P. Roske, Jr, Scientific and Technical Advisor, Force Structure, Resource and Assessment Directorate (J-8) of The Joint Staff. (Workshop attendees are listed in Appendix C.) Workshop attendees developed the warfare simulation taxonomy addressed below which they believe will be valuable for:

1. classifying warfare simulations,
2. constructing frameworks for comparing conflict models,
3. providing the foundation for a comprehensive wargames catalogue.

The workshop focused entirely on warfare simulations and did not devote attention to developing a classification system for other types of models, such as engineering models for weapons development, etc.

Two terms--"model" and "simulation"--have appeared repeatedly above and will recur continually below, and both need to be defined.

1. A model is a representation of a system
2. A simulation is:
 - a. a model
 - b. the exercise of a model
 - c. a Monte Carlo model

The four definitions of simulation are listed in order of preference and all are acceptable to mainstream wargamers (as acceptable as four definitions for a single word would be if found in a dictionary). In this paper, model and simulation are used interchangeably. Thus warfare simulation means a model of warfare or any part of warfare for any purpose (such as analysis or training).

It is important here, moreover, to point out the differences between a taxonomy and a catalogue. The former, a classification system, if it is valid, is an indispensable foundation for the latter, a collection of descriptions. But a taxonomy will not provide all the useful information one might want to know about a conflict model being described. Think for a minute about Charles Darwin's taxonomy of kingdom, phylum, class, order, family, genus and species. Marine biologists classify oysters though seven Darwinian levels without telling one that the marine, bivalve, mollusk

¹ Now the Force Structure, Resource and Assessment Directorate (J-8) of The Joint Staff.

from the family Ostreidae are tasty and that a dozen of them cost about \$8.00 at Clydes. A taxonomy provides the basis for classifying objects (such as an oyster or a warfare simulation) for identification, retrieval and research purposes and a catalogue provides additional, valuable information (such as set up time, running time, developer, point of contact, etc.)

With these ideas in mind, early workshop discussions were concerned with discovering the fundamental attributes and structures common to warfare simulations. Initial exchanges were based on a paper delivered by Lieutenant General John H. Cushman (USA-Retired) titled "On Representing Warfare." This paper was the product of a collective effort, sponsored by the Joint Analysis Directorate, by General Cushman, Wayne Hughes, Sam Parry and Michael Sovereign. The discussion that followed Gen Cushman's remarks provided insights which suggested that a classification system, or taxonomy, could be developed for warfare simulations.

The conference concluded that a taxonomy for warfare simulations needed to address three equally important, relational (as opposed to hierarchical) dimensions: the *purpose*, the *qualities* and the *construction* of the model or simulation. These three dimensions taken together were thought to be sufficient for classifying models, as is Darwin's taxonomy for classifying animals, but, while all three dimensions have beneath them subdivisions, each dimension is independent of the others. That is to say the entities found under any one dimension are not found under either of the other two dimensions. Unquestionably, however, the three dimensions are functionally related for one would find it impossible to describe clearly a model by reference to only one dimension of the warfare simulation taxonomy.

II. CLASSIFICATION BY PURPOSE

Describing the purpose of a warfare simulation explains why the model was built or to what use the model is being (or could be) applied. For example, the purpose of the SOTACA (State of the Art Contingency Analysis) model is analysis. Note that describing SOTACA's purpose says nothing about SOTACA's qualities nor about its construction (that is, what entities and processes are characterized).

Of course, models may be used for more than one purpose, but, this no more invalidates purpose as one dimension of the taxonomy than listing the numerous uses for a baseball bat might invalidate the definition one finds for that object in a dictionary. SOTACA's primary purpose is analysis, it could also be used for training. Most conflict models, however, can be described as having one purpose or the other. The workshop decided that model or simulation purpose could be subdivided into two major divisions: analysis or training and education (see Figure 1).

Analysis can be further subdivided into two branches, Research and Evaluation Tools, and Operations Support Tools (Figure 1). The Research and Evaluation Tools category can also be subdivided (see Figure 2) into categories dealing with Weapons Systems, that is, Systems Development or Systems Effectiveness against targets and their efficient mix with support systems. The taxonomy places force capability assessment and combat development applications in the Research and Evaluation category. "Combat Development" examines current doctrine, explores new doctrine, evaluates competing strategies or tactics, or studies various policies.

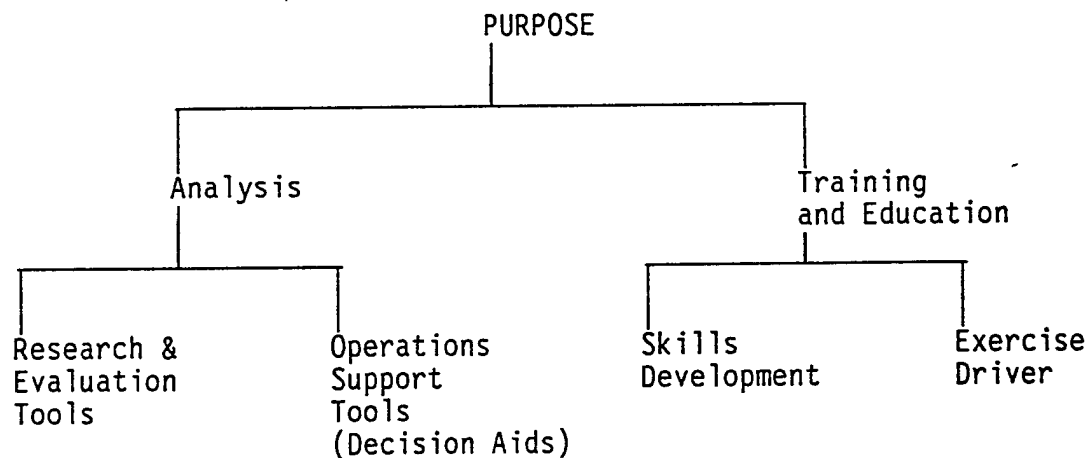


Figure 1. Purpose Taxonomy

A model used as an operations tool would support the decision making elements of operations, resource management, and support operations. In this category models find use as decision aids. Examples include automatic inventory reorder models or weight and balance models for loading aircraft.

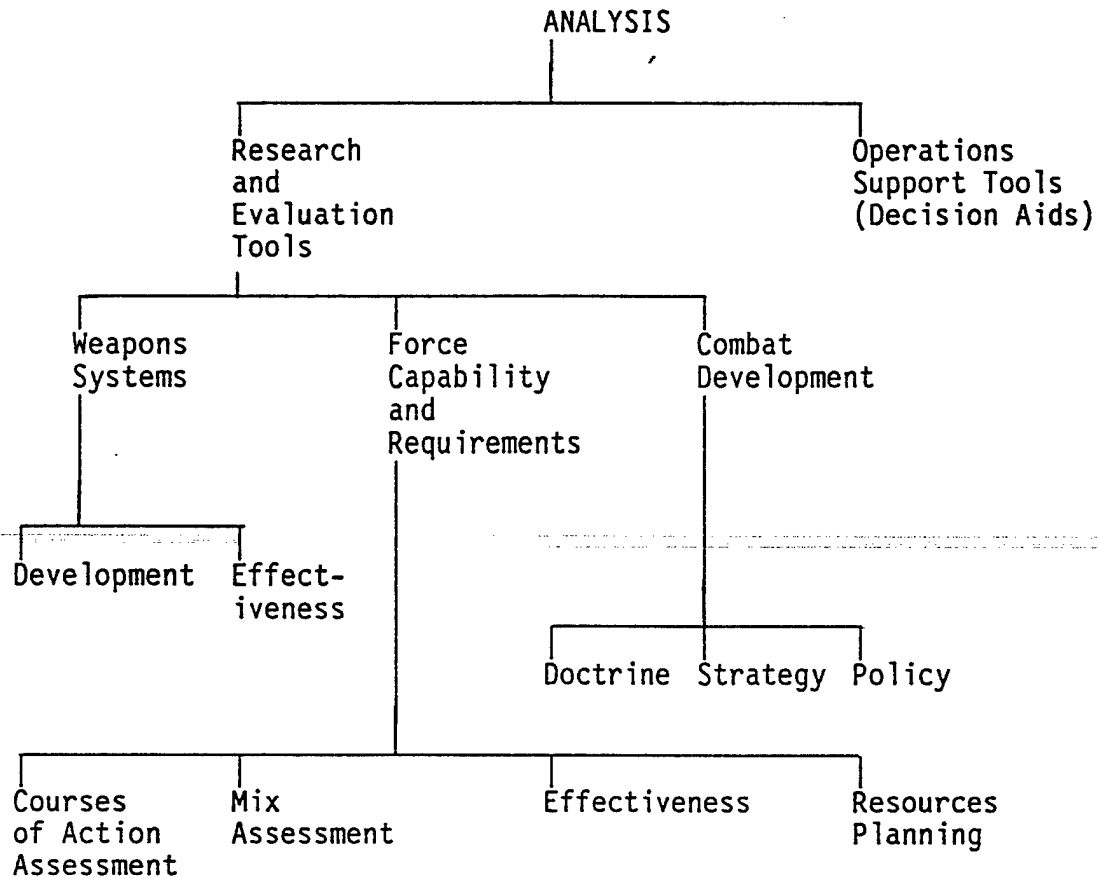


Figure 2. Analysis Expanded

Another broad *purpose* of conflict models and simulations is training and education. The subdivisions of this dimension are Skills Development on the one hand and Exercise Drivers on the other. These two categories can be further subdivided as illustrated in figure 3.

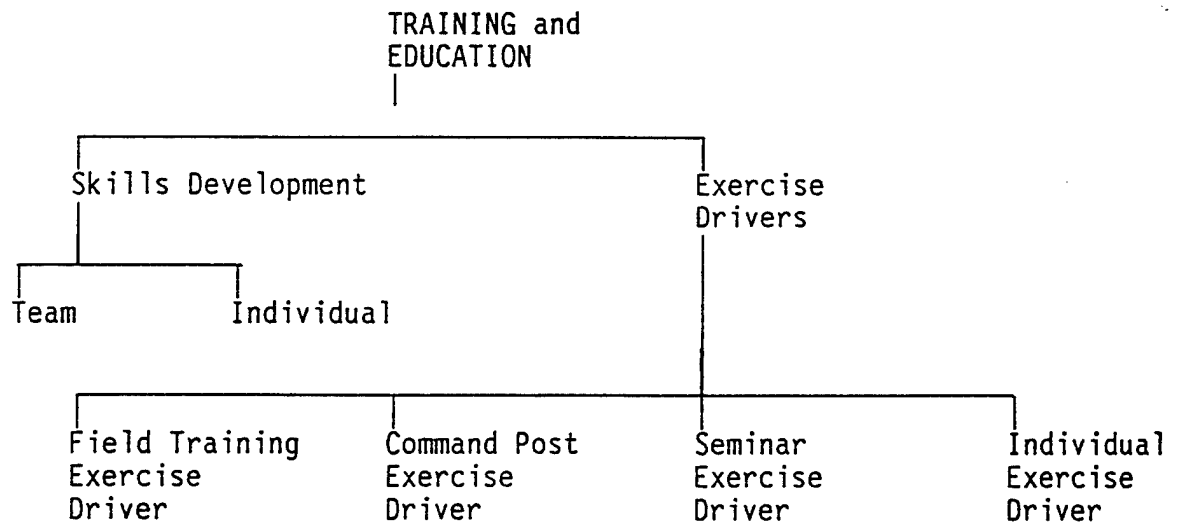


Figure 3. Training Expanded

The boundary between training and analysis is gray, and a guideline to differentiate between training and analytic uses of warfare simulations is useful. The authors believe military men, when not fighting in a war, seek to improve their own and their troops' proficiency in the conduct of war, or (and) they seek a better understanding of war. The former we call training and the latter we call analysis. In general, if the *purpose* of using a model is to transfer or reinforce a lesson or relationship that is already known, then the *purpose* is training or education. On the other hand, if the model is used to discover, deduce or expand relationships or lessons, then the *purpose* is analysis.

By these guidelines, if a commander uses a model to sharpen his command's skills or to teach subordinates some lesson, then the model is used for training and education. If, however, the commander uses the model to drive an exercise to explore the merits of alternative courses of action, then the model is being used for analysis. Unquestionably, and this point needs emphasis, many models can be useful for both analysis and training, even simultaneously. That is, a model used to drive a given exercise could be simultaneously used for both analysis and training by the same people.

III. CLASSIFICATION BY QUALITIES

The qualities dimension of a military model are those real entities and processes which the model represents. The following categories were defined and examined by the SIMTAX Workshop.

A. Domain

The physical or abstract space in which the entities and processes operate. The domain can be land, sea, air, space, undersea, a combination of any of the above, or an abstract domain, such as an n-dimensional mathematics space, or economic or psychological domains.

B. Span

The scale of the domain, that is global, theater, regional, local, individual. Description of the span is often subjective.

C. Environment

The texture or detail of the domain, that is terrain relief, weather, day, night, terrain cultural features (such as cities or farmland), sea states, etc.

D. Force Composition

The mix of forces that can be portrayed by the model, that is, combined forces, joint forces, component, element, etc. Processes such as logistics, communications, and intelligence as well as the composition of force entities work together to determine the force composition abilities of the model.

E. Scope of Conflict

The category of weapons, that is, unconventional, conventional, chemical, biological, nuclear, chemical-biological-nuclear, special, rear-area (either red or blue).

F. Mission Area

Recognized combinations of weapons and procedures used to accomplish a specific objective, that is, sea control, close air support, airlift, indirect artillery, etc.

G. Level of Detail of Processes and Entities

This category of the *qualities* dimension has two components: entities and processes. Regarding "entities", "level of detail" answers the questions, what is the lowest, discrete entity modeled (e.g. numbered air force, air division, wing, squadron, flight, individual aircraft; army, corps, division, brigade, battalion, company, platoon, squad, soldier; individual tank, tank-platoon, tank-company, etc., or individual ship, battle group, task force).

"Processes" affect entities. Attrition, communications, and movement are examples of processes. Processes have a level of detail by which they are described. For example, the attrition processing may be defined in shot-by-shot detail or as a generalized percentage reduction in a unit's resources as a consequence of coming in contact with an opposing unit.

The level of detail of an entity can vary within a model depending upon which process was acting on that entity. For example, armored vehicles might be represented as individual vehicles for attrition purposes, but might disappear as individual vehicles and receive orders to move as a larger unit such as an armored division. Description of the level of detail of a model must contain qualifiers addressing the processes in the model. (For a more detailed discussion of Level of Detail, including a mathematical description of Attrition calculation see Appendix A pages A-19 through A-25. For a graphic depiction of this concept see Figure 8.)

While the workshop listed several discrete categories of entities and processes which military models represent, the authors of this paper are sure the workshop did not examine all possible entities and processes. The authors hope their readers suggest additions to the Qualities dimension (through MORS), and, of course, welcome any suggestions for improving the taxonomy. The form at appendix B can be used for these purpose and also for testing the taxonomy.

IV. CLASSIFICATION BY CONSTRUCTION

Construction defines the design of the model. There are four major categories in the *construction* dimension:

A. Human Participation

The extent to which a human presence is allowed or required to influence the operation of the model. The two major divisions of this category are "required" and "not required." Each branch can in turn be further subdivided as indicated in Figure 4.

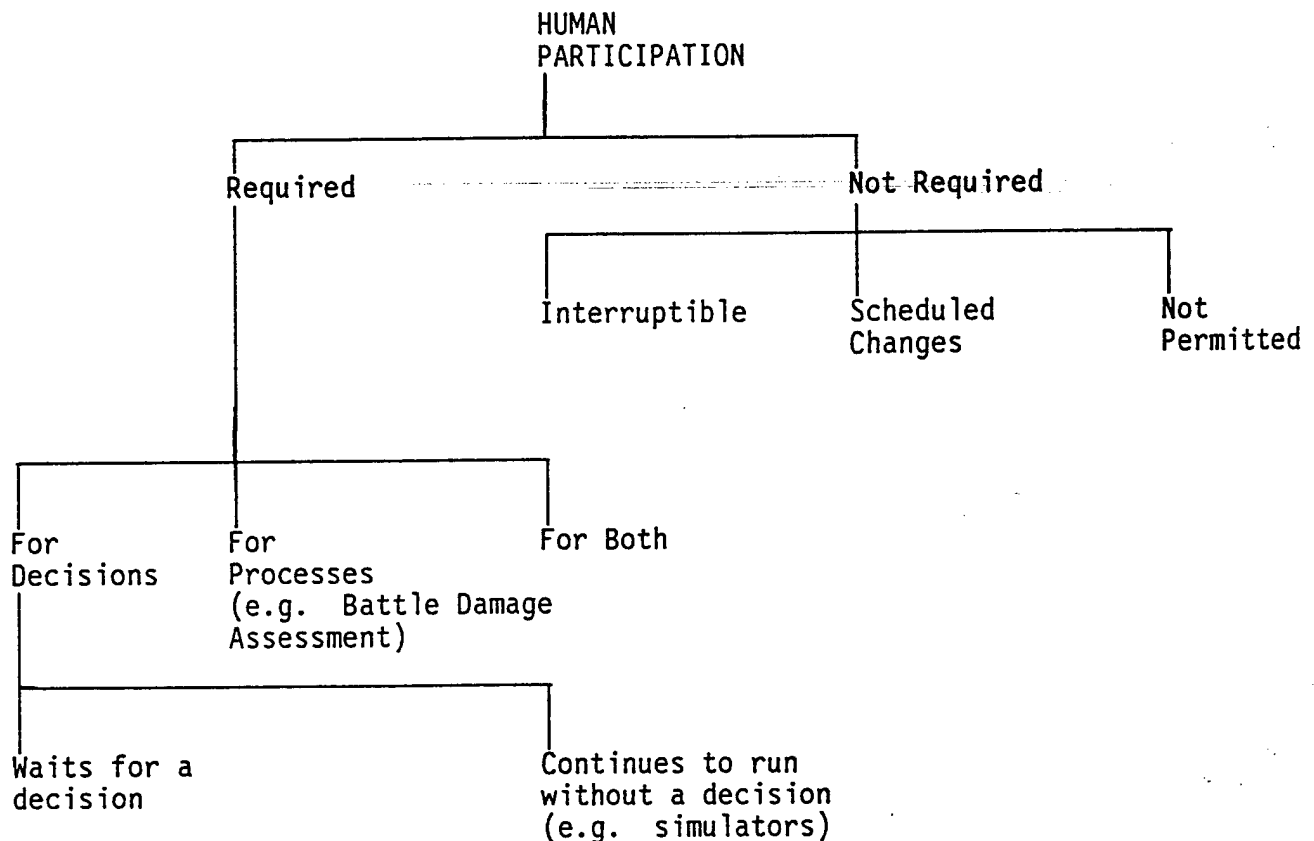


Figure 4. Human Participation

A lengthier discussion of Human Participation can be found in Appendix A on pages A-5 and A-6.

B. Time Processing

The two major divisions of model construction in this category are "dynamic," those models that treat time dependent processes, and "static," those that do not represent a dependence on time. "Dynamic" processes are further divided into "time step", "event step" or "closed form" models depending on the way in which the effect of the passing of time is calculated (see Figure 5).

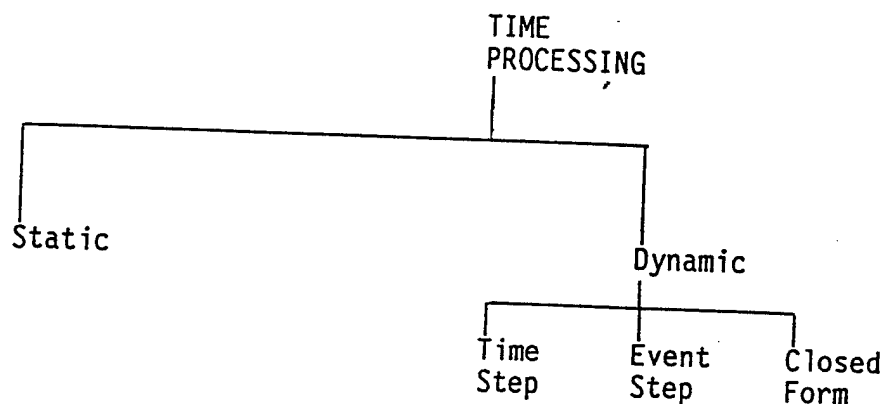


Figure 5. Time Processing

A lengthier discussion of Time Processing, complete with a mathematical description of Dynamic, Closed Form processing can be found in Appendix A pages A-7 and A-8.

C. Treatment of Randomness

Models which acknowledge and represent the possibility of various outcomes of the same event are classified as stochastic. Those models which do not represent variations in outcomes are classified as deterministic. Stochastic models are either Direct Computation or Monte Carlo models. The latter-type models may be Monte Carlo for some processes and not others, but if any part of a model is Monte Carlo the model is classified as a Monte Carlo model. Further subdivisions of each of these divisions are presented in Figure 6.

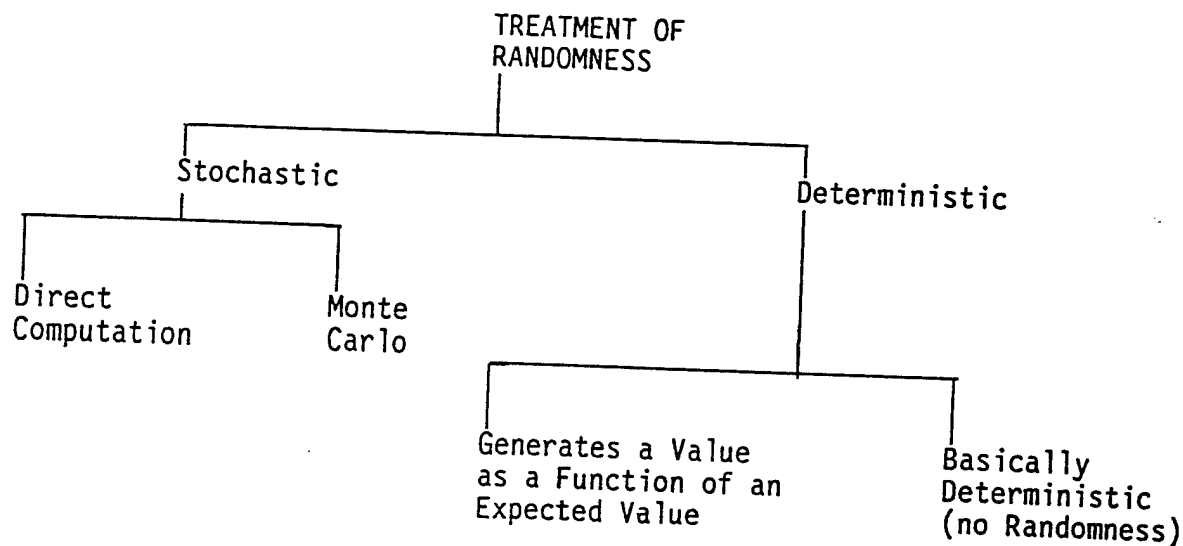


Figure 6. Treatment of Randomness

Randomness is examined in greater depth, including mathematical discussions of deterministic and stochastic processes in Appendix A on pages A-9 through A-13.

D. Sidedness

Refers to the number of collections or alliances of resources working in or through the model toward a common goal. Models are classified as being one, two, or three or more sided. Two sided models are classified as being symmetric, asymmetric, or one side non reactive. See figure 7.

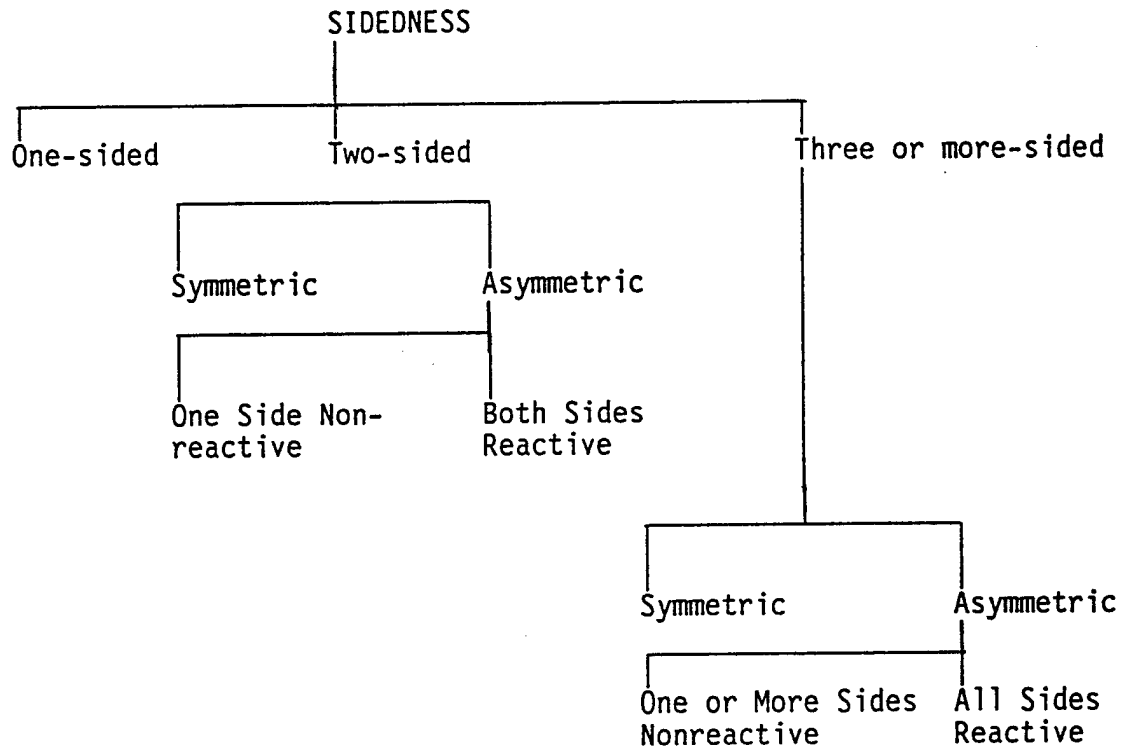


Figure 7. Sidedness

Sidedness is examined in greater depth in on pages A-15 and A-16.

Other categories of useful information dealing with the make up of the model, outside of the construction dimension, could be inserted into a catalogue. For example, one might consider such areas as specific references to documentation (e.g. author, Defense Technical Information Center acquisition number, etc.), programming language, what computers the model can be operated on, what is the speed of a typical run, etc. Catalogue users would also want to know the numeric methodology involved in the model, especially if the numeric methodology were special. Examples might be a linear program, a differential equation representation, or a Markov process, etc. Similarly, prospective users need to know if the model in the catalogue is related to or dependent upon another model. Some models may not be able to operate alone but may require the use of another model to provide inputs or perform "off line" types of calculations. The relationship between the Joint Exercise Support System (JESS) and the Tactical Simulation Model (TACSIM) is an example of this dependence.

V. CONCLUSIONS

The taxonomy described above allows one to classify models in such a way that one could group models by selected common characteristics, and then display in matrix form the voids and duplications in particular aspects of their purpose, qualities, or construction dimensions. For example, Figure 8 is a comparative architecture for three hypothetical models (A, B, and C) that have in common that they were built for the purpose of training and constructed as dynamic two sided, symmetric with human participation models that address the qualities of theater land warfare and can be formed into a framework that displays the level of detail (Division, Brigade, etc.) handled by various processes of interest (attrition, movement, etc.). Voids in this descriptive framework indicate areas in which none of the models with the common characteristics described address the indicated processes acting at the corresponding level of detail. The relationships displayed by these frameworks are of course the design prerogative of the user. There are potentially many descriptive frameworks.

COMMON CHARACTERISTICS

Purpose: training, team, exercise driver

Qualities: theater, land, combined force

Construction: dynamic, two-sided, human participation

		VARIABLE CHARACTERISTICS (Processes)			
		Attrition	Communi- cations	Movement	Resupply
V A R I A B L E C H A R A C T E R I S T I C S	DIVISION*	Model C	Model C	Model A Model C	
	BRIGADE*		Model A Model B		
	Unit Weapon System*	Model A Model B		Model B	

* See Appendix A, Pg. A-19

Figure 8. Sample Descriptive Framework

APPENDIX A

Methodological Aspects of Combat Modeling

I. INTRODUCTION

Several important methodological aspects of a defense-related model can be characterized in a relatively succinct manner by providing answers to the questions discussed below. Accordingly, the possible answers to these questions can be thought of as giving a type of taxonomy for defense modeling methodologies. Additionally, the brief but consistent approach for characterizing defense models described below can be quite useful in many circumstances, whether or not this method is viewed as a taxonomy for defense models.

The questions discussed below are of one of two forms. For one of the forms, the answers are in terms of "how much of the model is this way," where "this way" is described in the statement of the question, and "how much" is either a numeric measure or a list of representative examples. Questions in this form are called "descriptive questions" below.

For the other form, the questions have multiple choice answers, where the set of choices is defined in the statement of the question. The questions in this latter form are worded in such a way that no more than one answer can apply to any given model. These questions are referred to below as "categorical questions."

However, the people categorizing any given model are encouraged to subdivide the model into parts, where these parts are not necessarily clearly defined (a somewhat vague description would do), but are necessarily collectively exhaustive (which, when appropriate, might be easily done by calling one part "everything else"). This subdivision into parts could be made for some of the categorical questions but not for others and, when it is made, it need not be the same for each question--one subdivision might be more appropriate for one part of one question, a different subdivision could be more appropriate for a different part of that question, and yet other subdivisions could be used for other questions. A categorical question could then be answered for each part of the model as well as for the model as a whole. Some natural subdivisions for some of the questions are stated as part of those questions or are suggested in the discussions of those questions below.

II. HUMAN PARTICIPATION

The first question is the following categorical question: Is human participation required during the running of the model? Models that require human participation are sometimes called interactive or human-in-the-loop models, and may or may not use a computer. Models that do not require human participation are sometimes called fully automated models and, with one set of exceptions, seem to require the use of a computer (the one set of exceptions consists of simple mathematical models that have tractable closed-form solutions). If any portion of the model requires human participation during the running of the model, then the answer here is "yes." Only if the model can (perhaps optionally) be reasonably run with no mid-run human participation is the answer "no."

A. Human Participation Required

1. *Decisionmaking Only Versus Decisionmaking Plus Other Aspects Versus Other Aspects Only*

If human participation is required, is it required only to make (some of the) decisions that humans would have to make in real combat, or is it needed both for this decisionmaking and for other aspects of the model (such as to represent selected physical processes and/or to provide outcomes for selected combat interactions), or is it needed only for aspects other than this decisionmaking?

2. *Continuously Running Versus Pause and Wait*

If human participation is required, does the model keep running (in model time), simulating events as if no decisions were being made (as in a "Space Invader" or "Flight Simulator" type of computer game)¹, or, in at least one place, does the model pause and wait for human input (as in an adventure type of computer game or a chess game with no time limit)? If the model runs continuously in time, can realistic cases typically be run at speeds faster than real time (if so, how much faster?), or only at the same speed as real time, or only at speeds slower than real time (if so, how much slower?).

B. Human Participation Not Required

1. *Human Participation Not Allowed*

Does the model have the property that, for all practical purposes, not only is human participation not required, it is not even allowed?

2. *Human Participation Allowed Through Interruption*

A model might have the property that it can be interrupted in some manner (e.g., at a specified time, due to one of a specific set of events, or by a human who is watching the outputs as they are produced and "manually" interrupts the model). For an "interruptible" model, decisions and/or data changes can be included in the processing of the model when it is interrupted. The model can then be started from the point of the interruption. Whether or not a model is interruptible is a categorical type of question requiring a yes-no answer. However, the allowable set of decisions and/or data changes that can be made

¹ In such a case, if the model is run and no decisions are provided by humans, then the model typically provides degenerate outputs and meaningless results. This is in contrast to a model that does not require human participation and so can provide reasonable outputs and meaningful results if appropriately run without human interaction.

requires a descriptive answer. If the categorizer of a model states that the model is interruptible, then it would be useful to give also a brief description of what can and what cannot be changed during the interruption.

3. *Human Participation Allowed Through Scheduled Changes*

A model might have the property that some of its inputs are (optionally) changes to be made to certain data elements or of data to implement certain decisions at particular (model) times during the running of the model. With such a model, a user could run the model, look at the output, and decide that, say, through time t_1 , the outputs are appropriate, but at time t_1 the user wants to input a particular decision or change a particular set of data. The user could then schedule this decision and/or data change to be made at time t_1 , then restart the model and run it again, perhaps now deciding to accept the results through time t_2 (where $t_2 > t_1$), but to schedule another set of changes to occur at time t_2 , and so forth. Like interruption, if the categorizer of a model states that such scheduled changes are allowed, then it would also be useful to give a brief description of what types of changes can and cannot be scheduled.

4. *Both Interruption and Scheduled Changes*

Of course, a model might allow both interruption and the scheduling of changes.

5. *Other Techniques for Allowing Human Participation*

If it is believed that none of the above categories adequately describe a particular model, then that model can be grouped under this "all other techniques" category.

C. **Summary**

In the sense described above, a model either does or does not require human participation. If the model requires human participation, then either it does so only to represent human decisionmaking, or it does so both to represent human decisionmaking and for other purposes, or it does so only for other purposes. Further, such a model either is a continuously running model or is (in at least one place) a pause-and-wait (for the human participants) model.

If a model does not require human participation, it might preclude such participation entirely, or it might allow human participation by being interrupted, or by allowing scheduled changes, or both (or by other techniques).

III. TIME PROCESSING

As the discussion above indicates, an implicit methodological aspect of combat modeling is how the model treats changes that would occur to the status of resources over time. How a model treats time is a categorical-type of question in the sense described here.

A. Static Models

A static model is one in which the time-phased impact of changes in the states (or status) of resources is not explicitly considered. Such models lack a representation of time.

B. Dynamic Models

Dynamic models are the opposite of static models in that they do explicitly consider the time-phased impact of changes in the states (or status) of resources and they do incorporate a representation of time. In particular, dynamic models explicitly represent the passage of time, which they do in one of three ways: time runs continuously, time is incremented in (constant or non-constant) steps, or time is considered as part of a closed-form solution to a set of equations.

1. *Time Runs Continuously*

As stated above, a model can have the property that it continually simulates the passing of time, perhaps at a speed faster than, or equal to, or slower than the passage of real time, or perhaps at varying speeds.

2. *Steps Through Time*

A model that steps through time can either do so in steps of fixed or independently-determined size--such a model is called a time-step model--or it can build a list of significant (to it) events and, after it simulates one event, it steps directly to the time of the next event, no matter how long or how short that step in time is. This latter type of model (which steps from event to event) is called an event-step (or event-store) model. The terms "time step" and "event step" are defined more carefully below.

a. Time Step

The time step method for representing time in dynamic models is a method in which time is advanced by a fixed or independently-determined amount to a new point in time, and the states or statuses of some or all resources are updated as of that new point in time. Typically these time steps are of constant size, but they need not be.

b. Event Step

The event step method for representing time in dynamic models is a method in which selected events are scheduled in time, time is advanced to the occurrence of the next scheduled event, and the states or statuses of some or all resources (as well as the schedule of upcoming events) are updated at that point in time to reflect the occurrence of that event.

3. *Closed Form Solution*

A dynamic model can also be in the form of a set of differential (or difference) equations, which may have a closed form solution. A closed form solution for representing time in

dynamic models is a method in which the states or statuses of resources are described as explicit and computationally tractable functions of time. Thus, the status of a resource at, say, time t can be found by evaluating the appropriate function at t , without having to simulate combat (either in steps or continuously, as described above) from the start of that combat through time t . For example, given $b(0) > 0$ and $r(0) > 0$, the closed form solution of

$$dr(t)/dt = \begin{cases} -kb(t) & r(t) > 0 \\ 0 & r(t) = 0 \end{cases}$$

and

$$db(t)/dt = \begin{cases} -k'r(t) & b(t) > 0 \\ 0 & b(t) = 0 \end{cases}$$

for $t \geq 0$ is

$$b(t) = \begin{cases} b(0)\cosh\lambda t - \alpha r(0)\sinh\lambda t & t \leq \tau \\ b(\tau) & t > \tau \end{cases}$$

$$r(t) = \begin{cases} r(0)\cosh\lambda t - \alpha^{-1} b(0)\sinh\lambda t & t \leq \tau \\ r(\tau) & t > \tau \end{cases}$$

where

$$\lambda = (kk')^{1/2},$$

$$\alpha = (k'/k)^{1/2},$$

and where τ is given by

$$\tau = (1/2\lambda) \log \{ [(kb^2(0))^{1/2} + (k'r^2(0))^{1/2}] / [(kb^2(0))^{1/2} - (k'r^2(0))^{1/2}] \}$$

if this denominator is greater than zero, and by $\tau = \infty$ otherwise.

Few models are this simple, but the ones that are can be important, and they fit into this category.

C. Summary

In the sense described above, a model either is static or is dynamic. If it is dynamic it either processes time continuously, or it does so in steps, or it has a closed form solution. If it processes time in steps, it either does so in fixed time steps or it does so by stepping directly from the time of an event to the time of the next event being simulated.

IV. TREATMENT OF RANDOMNESS

Another important methodological aspect in the construction of a combat model is how the model treats random events. There are two basic approaches here. One is essentially to ignore randomness; this approach leads to deterministic models. The other approach is explicitly to consider randomness in some manner; this approach leads to stochastic models.

A. Deterministic Models

1. *Deterministic Models of Deterministic Processes*

For some processes, it is reasonable to assume that randomness plays an insignificant (or even non-existent) role. Such processes are inherently deterministic and, of course, it is appropriate that models of these processes be deterministic models.

2. *Deterministic Models of Stochastic Processes*

Many, perhaps most, military processes are stochastic, not deterministic, and so case (1) just above does not apply. However, it is possible to construct and use deterministic models of stochastic processes in the following manner.

First, the model is constructed so that resource-related quantities, such as the numbers of particular types of resources at particular locations, the numbers entering particular combat interactions, and the numbers surviving those interactions, are represented in the model by real-valued numbers (as opposed to by integers). For example, the model might account for an initially input number of aircraft on an airbase, and it might simulate that half those aircraft take off to fly a mission on which a tenth of them are killed due to enemy fire. This is as opposed to simulating particular events, such as that a particular (say, by tail number) aircraft takes off from a particular airbase and then either is or is not shot down by enemy fire.

In a stochastic model, this representation of events by real-valued numbers might lead to the consideration of random variables. For example, the number of a particular type of resources that survive their first combat interaction might be denoted by X . The way that the model processes these survivors might be denoted by the function f , so that the overall output would be the random variable $f(X)$. The expected value of this random variable could be denoted by $E[f(X)]$. However, properties of the random variable $f(X)$, such as its expectation $E[f(X)]$, are essentially impossible to compute in many cases, and so the stochastic approach of attempting to compute $E[f(X)]$ is useless for these cases.

A deterministic model can be used here, however, by replacing all random variables with deterministic quantities, such as their expectations or estimates of their expectations. For example, if the random number of resources surviving a particular interaction is given by the random variable X , then a deterministic model here would ignore the randomness and, instead, replace X by its expected value $E[X]$ (or by an estimate of $E[X]$). Such a model could then process the number $E[X]$ to compute $f(E[X])$. Of course, it is generally not true that $f(E[X]) = E[f(X)]$, but this approach does allow deterministic methods to be used to model complex stochastic processes in a computationally tractable (but not mathematically rigorous) manner.

In short, a deterministic model of a stochastic process is one that ignores the inherent randomness in the stochastic process by replacing all random variables with deterministic quantities (e.g., their expectations) during the running of the model.

B. Stochastic Models

There are basically two types of stochastic models. One uses the Monte Carlo method to produce a set of independent and identically distributed random outcomes. The other directly computes analytic properties of random variables representing those outputs, such as the mean or the whole distribution of those outputs.

1. Monte Carlo Models

A Monte Carlo model of a stochastic process produces, for each trial, one realization of the results of that process by drawing (pseudo) random numbers to determine realizations of (one or more) random variables being simulated by that model. Thus, a Monte Carlo model may have many deterministic aspects, and it may replace random variables by their expectations many times, but at least once it does not make this replacement. Instead, at least once it draws a (pseudo) random number to determine a realization of a random variable and it uses that realization as an input to the rest of the process simulated in the model. Each run through all of the processes simulated by the model is typically called a trial. If n trials are run, and if the realization of a random variable, say X , is x_i for the i th trial, then the model estimates the expected value of X , $E[X]$, by

$$E[X] \approx \sum_{i=1}^n x_i/n.$$

Clearly, this estimate can be very good for very large values of n , and can be very poor for very small values of n .

2. Direct Computation

The concept of a stochastic model that uses direct computation might be best described by giving an example. Picture a model of a combat engagement in which the following holds. There are two sides; however, only the resources on one of the sides can fire at the other side--the resources on the other side are targets only. Suppose that there are M types of shooters on the shooting side, with s_i denoting the number of shooters of type i ($i = 1, \dots, M$), and N types of targets on the target side, with t_j denoting the number of targets of type j ($j = 1, \dots, N$). Suppose the following:

- 1) At a fixed time all targets become vulnerable to detection and attack.
- 2) The probability that a particular shooter of type i detects a particular target of any type is d_{ij} for $i = 1, \dots, M$.
- 3) Out of all of the targets (of all types) detected by a shooter, that shooter chooses, according to a uniform distribution, exactly one to fire upon.
- 4) Given that a shooter of type i has detected and chosen to fire upon a target of type j , the shooter kills that target with probability k_{ij} , for $i = 1, \dots, M$ and $j = 1, \dots, N$.
- 5) A given shooter detects targets independently of one another.
- 6) A shooter detecting no targets does not fire.
- 7) The detection and firing processes of all of the shooters are mutually independent (so two different shooters can detect, choose to engage, and fire lethal shots at the same target--which results in one target being killed, not two).

Let Δt_j denote the number of targets of type j killed ($j = 1, \dots, N$).

If $M = 1$ and $N = 1$, let $s = s_1$, $t = t_1$, $d = d_1$, $k = k_{1,1}$, and $\Delta t = \Delta t_1$. Then (for $n = 0, 1, \dots, t$) it can be shown that the assumptions listed above imply that:

$$\text{Prob}\{\Delta t = n\} = {}_t C_n \sum_{m=0}^n (-1)^{n-m} {}_n C_m [(1-q_t) + (q_t m/t)]^s$$

where

$${}_x C_y = x! / ((x-y)! y!)$$

and

$$q_t = q_t(d, k) = k[1 - (1-d)^t].$$

Also, if $M = N = 1$, then:

$$E[\Delta t] = t(1 - [1 - (k/t)(1 - [1-d]^t)]^s).$$

For general (integer) M and N , the computation of

$$\text{Prob}\{\Delta t_j = n\}$$

for all relevant n is not tractable; however, $E[\Delta t_j]$ can be computed (for $j = 1, \dots, N$) as:

$$E[\Delta t_j] = t_j (1 - \prod_{i=1}^N [1 - (k_{ij}/u)(1 - [1-d_i]^u)]^{s_i})$$

where

$$u = \sum_{j=1}^N t_j.$$

This is a very simple model--it only models one engagement and it only allows one side to shoot; but it is a stochastic model that computes results directly, instead of by using a Monte Carlo method. The case in which $M = N = 1$ is sufficiently simple that the entire distribution of the random variable Δt can be calculated. The case for general M and N is too complex to allow direct computation of the distribution of Δt_j , but its expectation, $E[\Delta t_j]$, is readily computed as indicated above.

As this example shows, a model can treat randomness by providing tractable formulas to properly compute relevant quantities associated with the stochastic process being modeled. These quantities might only be the expected values of relevant results, or they might include higher moments, or (as in the $M = N = 1$ case above) they might include the entire distribution. The important point here is that randomness can be directly addressed by stochastic models that do not draw any random numbers and so are not Monte Carlo models. Such non-Monte Carlo stochastic models belong in this "direct computation" category.

C. Summary

The way that one part of a model treats randomness can be (and frequently is) quite different than the way that a different part of the same model treats randomness. Accordingly, this is an area in which it can be useful for the categorizer of a model to subdivide the model into a judgmentally selected set of collectively exhaustive parts, and to categorize these parts separately as to their treatment of randomness.

The question of how a model (or any part of a model) treats randomness is a categorical type of question in the sense described above. Determining the proper category is easy for some cases, but can require a significant amount of understanding and judgment for others.

If any part of a model draws even one random number for use in determining a realization of a random variable (i.e., uses the Monte Carlo method), then that part is Monte Carlo, and if any part of a model is Monte Carlo then the model as a whole is Monte Carlo. It is sometimes tempting to say that a model is not really a Monte Carlo because it draws just a few random numbers per trial and most of the code concerns deterministic modeling, but this is not helpful information since it applies to most (if not all) Monte Carlo models. That is, much of any Monte Carlo model is devoted to aspects other than drawing random numbers. However, if even one random number is drawn, then multiple trials of the model need be run for any statistical validity. Further, if a model draws one or more random numbers and so requires running multiple trials, but treats a particular quantity in a deterministic manner, then it can be quite easy to modify that model to treat that quantity in a Monte Carlo manner and the modified model would be (in general) as easy to run and use as the original. The same statement cannot be validly made about a model that draws no random numbers.

According to this rule (whether or not it draws one or more random numbers), it is easy to classify a model as to whether it is Monte Carlo or not.

If a model: (a) does not draw any random numbers, (b) considers probabilities of various events occurring and/or distributions of various random variables, (c) replaces one or more of the major random variables resulting from these probabilities or distributions by deterministic quantities (such as the expectations, or estimates of the expectations, of these random variables), and (d) makes significant use of one or more of these expectations by further processing of the model, then the model is a deterministic model of a stochastic process.

If a model neither draws random numbers nor considers probabilities of events occurring and/or distributions of random variables because the processes it is modeling can reasonably be considered to be essentially deterministic, then the model is a deterministic model of a deterministic process. However, if a model neither draws random numbers nor considers probabilities of events occurring and/or distributions of random variables, but it could reasonably do so because the process being modeled has inherent and significant stochastic variables, then the model is a deterministic model of a stochastic process as discussed above.

If a model: (a) does not draw any random numbers, (b) considers probabilities of selected events occurring and/or distributions of selected random variables, (c) treats other quantities (if any) as deterministic because these other qualities can reasonably be considered to be essentially deterministic, (d) properly computes selected statistical properties (such as the mean, or the mean plus some higher moments, or the entire distribution) of significant random variables resulting from the probabilities or distributions it addresses, then the model is a stochastic model that uses the direct computational method. However, if condition (c) just above fails because the quantities assumed to be deterministic have, in fact, inherent and significant stochastic variations that, if properly considered, could significantly affect major statistical properties of the results, then the model in question is a deterministic model of a stochastic process.

With this structure, and with some judgment where necessary, models can be classified as belonging to exactly one of the four categories: stochastic models that use the Monte Carlo

method, stochastic models that use direct computation, deterministic models of deterministic processes, and deterministic models of stochastic processes. If a model is subdivided into parts, then each part can also be classified this way. Further, classification of all of its (collectively exhaustive) parts gives the overall classification of the model according to the following rule. If any part is Monte Carlo, then the whole model is Monte Carlo. If no part is Monte Carlo, but one or more parts are deterministic models of stochastic processes, then the whole model is a deterministic model of a stochastic process. If no part is either Monte Carlo or a deterministic model of a stochastic process, and one or more parts of the model are stochastic (sub)models that use direct computation, then the whole model is a stochastic model that uses direct computation. Finally, if all of the parts of the model are deterministic (sub)models of deterministic processes, then the whole model is a deterministic model of a deterministic process.

V. SIDEDNESS

A side in a defense-related model can be thought of as a collection of resources that are being used in cooperation to achieve common goals.

A. One-Sided Models

If all of the resources simulated in a defense-related model belong to one side, then that model is termed a one-sided model here. For example, some logistical models might fit into this category.

B. Two-Sided Symmetric Models

A defense-related model is termed a two-sided symmetric model here if the following three conditions hold: First, each resource simulated by the model belongs (in some sense) to one of exactly two sides. Second, if the model can simulate a particular type of resource (on one side) that can perform a particular set of operations at certain levels of effectiveness for that side, then it also must allow (though, of course, not necessarily require) the other side to possess resources of the same generic type that can perform the same set of operations at the same levels of effectiveness for that other side. Suppose a model can simulate a particular type of interaction between resources of one type (say type X) on one side (say side 1) and resources of a second type (say type Y) on the other side (say side 2). Then by this second condition it must also be able to simulate a type of resource corresponding to X, say X', on side 2 and a type of resource corresponding to Y, say Y', on side 1. The third condition is that, in this case, the model must also be able to simulate that same type of interaction between resources of type X' on side 2 and resources of type Y' on side 1 that it simulates between resources of type X on side 1 and of type Y on side 2.

These conditions might sound quite restrictive. However, in practice, they may not be unduly restrictive in that models tend either to satisfy all three conditions or to be fundamentally asymmetric in that they are quite far from satisfying these conditions. Accordingly, it can be informative to know whether or not a model is a two-sided symmetric model in the sense described here.

Again, it should be noted that allowing symmetry in the modeling of weapons and their operation does not mean that this symmetry occurs in any particular run of the model. Asymmetrical data can be (and usually are) used to model asymmetric scenarios. Symmetry of the model only means that the model is sufficiently flexible to optionally allow either side to use a particular set of weapons systems and/or tactics if the model allows the other side to use similar weapons systems or tactics.

C. Two-Strike Strategic Models

Before discussing two-sided asymmetric models, it is useful to distinguish an important class of models that have the properties that they are two sided and asymmetric, but (in a sense) are conceptually akin to two-sided symmetric models. This special class of models consists of two-strike strategic models.

Two-strike strategic models are, in general, asymmetric in that the first striker can fire at a combination of both value targets and force targets, while the second striker generally can only return fire (with whatever force it has remaining) against the first striker's value. However, there is an essence of symmetry here in that both sides are firing at the reasonable set of targets that they face--it is just that the reasonable set of targets for the second striker consists only of the first striker's value.

One-strike strategic models are clearly asymmetric and belong in the class of two-sided asymmetric models discussed next. Multiple (three or more) strike strategic models are relatively rare and can be adequately categorized by dividing them into those are purely symmetric (each strike, when it fires, can fire at any combination of remaining enemy resources) and those that are not symmetric.

D. Two-Sided Asymmetric Models

If a two-sided defense-related model is neither symmetric (in the sense described in Section 2 above) nor is a two-strike strategic model, then it is termed a two-sided asymmetric model here. Two-sided asymmetric models can be further subdivided into two types: nonreactive and reactive.

1. Nonreactive

A two sided defense-related model is termed nonreactive if one side is firing at the other and the other side is neither firing back nor taking any action to prevent being detected or hit, or to mitigate damage in any way. That is, if (in the model) the fired-upon side can only be doing whatever it would otherwise have been doing had it not been being attacked, then the model is nonreactive.

2. Reactive

A defense-related model is reactive if it is a two-sided asymmetric model but is not nonreactive in the sense just given. For example, all two-sided asymmetric models in which each side can shoot at the other in some manner are reactive models as defined here.

E. Three or More Sided Models

Other defense-related models, such as models that simulate three or more distinct sides, fit into this category.

F. Summary

With the structure presented above, all defense-related models belong to exactly one of the following categories: one-sided, two-sided asymmetric (other than two-strike strategic), two-sided two-strike (asymmetric) strategic, two-sided symmetric, and other. Accordingly, the question of sidedness is a categorical-type of question. As indicated above, it can be useful for a categorizer of a model to subdivide the model into collectively exhaustive parts for such categorical questions, and this comment certainly applies here. For example, a model may be two-sided symmetric in all respects except for the way that it models decisionmaking, or except for the way that it models logistics, etc. In such cases, the model as a whole would be two-sided asymmetric, but major parts of it might be two-sided symmetric. A categorizer who is willing to divide the model into parts could point this out by classifying the sidedness of each of the parts as well as classifying the model as a whole.

VI. NUMBERS OF RESOURCES INVOLVED

Some two-sided models are reasonably characterized as being one-on-one models; e.g., one-on-one duels. Others can be characterized as being few-on-few models in that the number of major resources on each side must be some reasonably small number, say less than or equal to six. Still others can be many-on-many in that the model can simulate more than, say, six major resources on each side. (Note, what is being considered here is the total number of major resources being simulated, not the number of types of resources.) Major resources here should be taken to mean weapons systems such as ships, aircraft, or armored vehicles (as opposed to munitions for these weapons systems). This structure can be made into a set of categorical questions as follows.

A. Numbers of Resources in One-Sided Models

If the model in question is a one-sided model, is the maximum number of major resources that it can simulate on that one side given by: (a) one, (b) 2 through 6 (i.e., few), or (c) 7 or more (i.e., many)?

B. Numbers of Resources in Two-Sided Symmetric Models

If the model in question is a two-sided symmetric model, is the maximum number of resources that it can simulate on each side given by: (a) one (i.e., one-on-one), (b) 2 through 6 (i.e., few-on-few), or (c) 7 or more (i.e., many-on-many)?

C. Numbers of Resources in Two-Strike Strategic Models

If the model in question is a two-strike strategic model, then it probably is a many-on-many model in that 7 or more major resources can be simulated on each side. Simply to allow for other possibilities, such a model can be categorized as being either (a) many-on many, or (b) something else.

D. Numbers of Resources in Two-Sided Asymmetric Models

If the model in question is a two-sided asymmetric model, then is the maximum number of resources that it can simulate on the "larger or equal" side followed by the maximum number it can simulate on the "smaller or equal" side given by: (a) one-on-one, (b) few (2 to 6)-on-one, (c) many (7 or more)-on-one, (d) few-on-few, (e) many-on-few, or (f) many-on-many?

E. Numbers of Resources in Three or More Sided Models

If the model in question simulates three or more sides (in the sense given above), then is the maximum over all sides of the maximum number of resources that it can simulate on a side given by (a) one, (b) 2 through 6 (few), or (c) 7 or more (many)?

VII. LEVEL OF DETAIL

In contrast to the categorical questions above, it seems better to structure level of detail questions in a more free-flowing descriptive form.

Questions concerning level-of-detail can apply to: (a) the types of resources that are simulated and the characteristics of these resources that are addressed, (b) the method of accounting for these resources, (c) the structure by which these resources are modeled, and (d) the structure in which these resources are located.

A. Types and Characterization of Effectiveness of Resources

The first descriptive question here is: What are some representative entities (systems) that are characterized by distinct effectiveness parameters in the model; and, for each such entity, what is an estimate of the number of parameters that the model uses to represent the effectiveness of that entity?

Some examples of entities that might be assigned distinct effectiveness parameters in a model of conventional combat are given in Table A-1.

In determining an estimate of the number of effectiveness parameters that the model uses for an entity, the following points should be noted. First, pure descriptors (like an entity's name or organizational attachment) should not be counted as effectiveness parameters. Second, characteristics of entities that, in reality, might affect the capabilities of a system, but do not do so in the model, should also not be counted here as effectiveness parameters. Third, multiple effectiveness parameters whose only role in a model is in a sum or product with each other should be counted as only one parameter. For example, if a model simulates the effectiveness of an entity by giving it a probability of detection, d , a probability of acquisition and fire given detection, a , a probability of hit given acquisition and fire, h , and a probability of kill given hit, k , and if the only places that d , a , h , and k are meaningfully used in the model is in the product $p = dahk$, then this entity is being described by one effectiveness parameter here, not four. As another example, if a model simulates the effectiveness of an entity by giving it an anti-personnel firepower, p , an anti-truck firepower, t , an anti-light armor firepower, i , and an anti-heavy armor firepower, h , and if the only places that p , t , i , and h are meaningfully used in the model is to determine the overall firepower of the entity by the formula $f = p + t + i + h$, then this entity is also being described by one effectiveness parameter here, not four.

B. Accounting for Resources

The entity structure used in a model for characterizing the effectiveness of resources need not be (and, in general, is not) the same as the structure used by the model to account for the resources themselves, and either one or both can differ from the structure used by the model to move resources. In particular, different entries in Table A-1 can be considered as giving different examples of entities that might be used to account for resources or to move resources. Some additional hypothetical examples are given in Section D, below, after structures to account for resources are discussed here and structures to move resources are discussed in Section C.

There seem to be five typically used methods to account for resources in models, and different resources can be accounted for using different methods in the same model. These five methods are as follows.

First, weapons systems can be accounted for individually. For example, a model could

Table A-1. EXAMPLES OF ENTITIES THAT A MODEL OF CONVENTIONAL COMBAT MIGHT CONSIDER

Entity Described	Army Examples	Navy Examples	Air Force Examples
1. Typical Groups of Weapons Form an Entity	Armored Divisions or Battalions	Generic Task Forces or Surface Action Groups	F-15 Squadrons or Flights
2. Particular Groups of Weapons Form an Entity	Particular Divisions or Battalions	Particular Task Forces or Surface Action Groups	Particular Squadrons or Flights
3. Weapons in the Same Generic Class Form an Entity	Armored Vehicles or Tanks	AAW Ships or Escorts in General	Aircraft or Fighters
4. Weapons of the Same Type Form an Entity	M60s, or M60A1s and M60A3s	CG-47 Class Ships and DDG-2 Class Ships	F-15s and F-16s
5. Each Particular Weapon Is an Entity	Individual Tanks	Individual Ships	Individual Aircraft

account for each tank, each ship, or each aircraft individually, knowing whether that particular weapons system is undamaged, damaged, or destroyed and, if not destroyed, where it is located.

Second, a model could account for numbers of weapons systems by type of system and by individual unit the system belongs to, but not by individual system. For example, a model might distinctly account for each battalion being simulated, knowing where that battalion is located and how many weapons systems, by type, are in that battalion (as well as how many systems belonging to that battalion have been damaged or destroyed); but it would not distinctly account for each individual weapons system in any particular battalion.

Third, a model could account for numbers of weapons systems by type of system, but not by individual system and not by individual unit that the system belongs to. For example, a model could account for the numbers of tanks, or of M60s, or of M60A3s, that are undamaged, damaged, and destroyed, and how many are located in a general area; but not how many tanks belong to any particular unit, not how many tanks belonging to any particular unit have been lost, not which particular tanks have been lost, and not where any particular tank is located.

Fourth, a model could account for groups of weapons systems by particular unit, but not either by particular system or by type of system within that unit. For example, a model could distinctly account for each battalion being simulated, knowing where that battalion is located and (say) how much firepower (according to some aggregated measure of firepower) is currently possessed by that battalion, but not which particular weapons or types of weapons are currently providing that firepower for that battalion.

Fifth, a model could account for groups of weapons systems by generic types of units, but not by particular unit nor by particular weapons or types of weapons with that generic type of unit. For example, a model could account for the number of armored battalions and the number of mechanized infantry battalions, how many battalions of each type are in each general location and knowing the average firepower of each type of battalion in each location, but not the location or firepower of any particular battalion and not which particular weapons or types of weapons are providing that firepower.

Of course, other (less frequently used) accounting methods are possible.

The descriptive question here is to estimate how many (either in terms of absolute numbers or of percentages or both) of the resources simulated in a model are accounted for by each of the five methods (or by "other") as described above and, if a mix of methods is used, to briefly describe which resources are accounted for by which method.

C. Movement of Resources

Clearly, resources cannot be moved using structures that are more detailed than the structures used to account for these resources, and resources can always be moved using the same structure as the structure used to account for them. However, resources can sometimes be moved using structures that are more aggregated than the structures used to account for these resources. In particular, the following ways to move resources can be considered.

First, if resources are accounted for individually, then they can be moved individually.

Second, if resources are accounted for either (a) individually, or (b) by type within particular units, or (c) by particular units but not by individual type of resource within these

units, then they can be moved by moving particular units. That is, if individual units are distinctly accounted for, then resources can be moved by moving those units (whether or not resources are either accounted for or can also be moved using other structures).

Third, if resources are accounted for by type of resource but not by type within a particular unit, then they can be moved by type. For example, a model that accounts for tanks in reserve and tanks in combat might (attempt to) move tanks so that a ratio of two tanks in combat for each tank in reserve is maintained.

Fourth, if resources are accounted for either (a) by type of resource, but not by type within a particular unit, or (b) by type of unit but not by particular unit and not by particular weapon or type of weapon within those types of units, then resources can be moved by moving units by type of unit. For example, if a model accounts for the number of armored battalions in reserve and the number in combat, then resources can be moved from reserve to combat in the model by decreasing the number of armored battalions in reserve by one and increasing the number of these battalions in combat by one.

Again, other (less frequently used) methods for structuring movement are possible.

The descriptive question here is to estimate how many (either in terms of absolute numbers or of percentages or both) of the resources simulated in a model can be moved by each of the four methods (or by "other") as described above and, if a mix of methods is used, to briefly describe which resources can be moved by which methods.

D. Some Hypothetical Examples

A model that distinctly accounts for each individual battalion being simulated, that measures the effectiveness of these battalions by assigning each a firepower score (which may be degraded through attrition), that moves resources by moving these battalions, but that does not account for or measure the effectiveness of individual systems or types of systems within these battalions is, in one sense, a battalion-level model. Conversely, it might not be considered to be a battalion-level model because it cannot simulate the inner workings of a battalion. Further, if the employment of the battalions in the model can span the width and depth (on both sides) of the theater, and if sufficiently many other resources (such as aircraft) are also represented so that the model can reasonably simulate many days of combat throughout the theater, then the model is, in a sense, a theater-level model.

Now consider a model in which very detailed type of weapons systems (M60A3 tanks, M101A1 howitzers, etc.) can be described by distinct effectiveness parameters, in which weapons are accounted for by these types, not by individual weapons or as being part of particular units, and in which (ground) weapons are grouped into four classes (direct fire weapons, indirect fire weapons, short range air defense weapons (SHORADs), and high/medium altitude air defense weapons (HIMADs)) for the purpose of accounting for movement (i.e., 67% of direct fire weapons and SHORADs, 90% of indirect fire weapons, and 60% of HIMADs are to be in combat, the rest are to be in reserve). Such a model in some senses (such as weapons effectiveness) is more detailed than the battalion-oriented model described above, yet is less detailed in other senses.

Finally, consider a model in which individual weapons are distinctly accounted for, but the effectiveness of these weapons must be described in terms of a relatively small number of weapon types that can be given distinct effectiveness parameters, and in which the (ground) weapons must be assigned to particular divisions and the only way to move these weapons is to move their divisions. Then, in some sense, this model is more detailed, in other senses it is in-between in detail, and in still other senses it is less detailed than the other two models

described above.

The point of these hypothetical examples is not that any of these types of models are necessarily better, more aggregated, more useful, more detailed, worse, less aggregated, less useful, or less detailed than the others. Instead, the point is two-fold. First (and less importantly), a particular model can treat different structural aspects (effectiveness, accounting, movement) at very different levels of detail. Second (and more importantly), it may not be possible to usefully define level of detail (or of aggregation) in a few words. If the concept of level of detail is sufficiently important to merit consideration, then it may require careful and somewhat extensively structured consideration.

E. Locations of Resources

As portions of the discussion above indicate, another aspect of the level of detail of a model concerns the structure that the model uses to represent the location of resources. In some reasonable sense, all resources can be located in two dimensions. Aircraft (including helicopters), submarines, and missiles also can be located in the third dimension.

1. *All Resources (Two-Dimensional Locations)*

a. Generic Structures

There are several structures that models can use to locate resources in two dimensions. Some common structures are as follows:

- (1) exact two-dimensional coordinates,
- (2) convex polygons (with specific location within a polygon being unspecified) where:
 - (a) the convex polygons are congruent squares,
 - (b) the convex polygons are congruent hexagons,
 - (c) the convex polygons are other types of polygons, perhaps being of varying sizes and shapes (e.g., various sizes of rectangles,
- (3) one dimensional subdivisions (into lengthwise or widthwise regions) with no subdivision in the other dimension (and with specific location within a region being unspecified),
- (4) no subdivision in either dimension (i.e., locations are not simulated),
- (5) other structures.

The descriptive question here is to give how many (either in terms of absolute numbers or of percentages or both) of the resources simulated in a model are located using each of these structures and, if a mix of structures is used, to briefly describe which resources are located by which structures.

b. Approaches that Use Convex Polygons

A second question here concerns only those models that use convex polygons to locate resources. Such models tend to use convex polygons in conjunction with one of two approaches.

In one approach, the polygons are relatively small (indeed, they may be nested inside of larger polygons), they are defined in terms of absolute geographical location (not in terms of locations relative to a line separating the forces on each side), and they are used both to

locate resources and to delineate the geographical characteristics of the areas they contain. Mobile resources can be moved from polygon to any adjacent polygon in order to surround an enemy and/or attack it from more than one direction. Frequently, the polygons used for this approach are congruent hexagons, and so this approach is sometimes called a "hex" approach. However, other polygons could be used--for example, rectangles (be they congruent squares or not), or an alternating pattern of octagons and (smaller) squares. Good automated movement rules (i.e., rules that never use worse decisions for better forces according to meaningful measures of effectiveness) are difficult to construct for models that use this approach. On the other hand, this approach is quite natural for interaction with human participants (e.g., it is frequently used in military board games and strategy-type computer games). Accordingly, models that use this approach tend to require human participation.

The other frequently used approach is as follows. Two (overlapping) sets of polygons (usually rectangles) are defined, where each set covers the area of interest. One set is used to locate forces for combat interactions; the other set is used to determine terrain and to locate fixed resources, such as aircraft shelters. The polygons used to locate forces tend to be relatively large (e.g., ranging from corps wide to theater wide and from fifty to several hundred kilometers deep), they can be defined in terms of locations relative to a line separating the forces on each side (and so they move as this line moves), and they tend to be generally structured like subdivisions of a set of parallel corridors (which run perpendicular to this line of separation). While forces can be moved sideways from corridor to corridor, once in a corridor they can only engage in combat those enemy ground forces across from them in the same corridor. Terrain and fixed resources are delineated using subdivisions of these corridors that are fixed in terms of absolute locations and tend to be finer-grained than the relative subdivisions used for locating forces for combat. Due partly to the corridor structure and partly to other aspects of ground combat, this approach has sometimes been called a "piston" approach when it is used in conjunction with ground combat. In general, this approach is relatively more frequently used in models that do not require human participation than in those that do require humans to make decisions concerning the movement of forces.

Referring to the first approach described above as a hex-type approach (even though polygons other than hexagons can be used) and to the second approach as a corridor-type approach, the relevant question here is, if a model uses convex polygons to locate resources, does it do so using:

- (a) a hex-type approach,
- (b) a corridor-type approach,
- (c) a mix of these approaches, or
- (d) some other approach?

2. *Aircraft, Missiles, and Submarines*

Aircraft (including helicopters), missiles, and submarines (as well as any other resources whose location can meaningfully vary in three dimensions) also can be located in the third dimension. Some common structures used are as follows:

- (1) exact altitude/depth,
- (2) subdivision into altitude/depth regions (with specific location within region remaining unspecified),
- (3) no third-dimension used,
- (4) other.

The descriptive question applies concerning the third dimension here is directly analogous to the descriptive question concerning two-dimensional locations described above.

VIII. ATTRITION DUE TO ENEMY FIRE

A. Attrition Not Assessed

Many models simulate some resources that are not subject to attrition due to enemy fire in the model. The first question here is to list and/or briefly describe such resources. The question of the resources simulated (if any) would then be subject to attrition due to enemy fire in the model.

B. A Taxonomy of Attrition Mechanisms

Some resources might be subject to attrition only once per time period due to one enemy weapon. Other resources might be subject to attrition in several different interactions with (perhaps) different sets of enemy weapons in each time period. The question here is that whether or not a resource is subject to attrition in a model is a property associated with that resource in that model. However, if a resource is subject to attrition, then how that attrition is assessed can also depend on the interaction (e.g., on the weapon causing the attrition) in question, not just on the resource, and different techniques can be used to assess attrition in different interactions.

The following is a mutually exclusive and (with "other" at the end) collectively exhaustive list of techniques that can be used to assess attrition in each interaction in which attrition is assessed.

1. Monte Carlo Techniques

Monte Carlo models can use Monte Carlo techniques to assess attrition. Indeed, many models are structured as Monte Carlo models primarily in order to allow them to assess attrition in this manner. Typically, such models simulate interactions in which a particular weapons system on one side is engaging a particular resource on the other side and a random number is drawn to determine the outcome of the engagement. Of course, other Monte Carlo structures are possible. For example, if a group of m shooters is engaging a group of n essentially identical targets and if it is postulated (either directly or indirectly) that the probability distribution of the outcome is that exactly i of the n targets will be destroyed with probability p_i (for $0 \leq i \leq n$), then a random number, r , could be drawn and the targets would be killed if j is such that

$$p_0 + \dots + p_j > r \geq \begin{cases} p_0 + \dots + p_{j-1} & j \geq 1 \\ 0 & j = 0. \end{cases}$$

The taxonomical structure here is that, if a model draws a random number in order to assess attrition in an interaction, then that model is using a Monte Carlo method to assess this attrition no matter what other techniques are used in conjunction with this random draw to determine the attrition.

2. Traditional Lanchester Square (Differential and Difference) Equations

a. Homogeneous Equations

The equations in Section III.B.3 above are the traditional homogeneous Lanchester square equations in their differential equation form. For the purpose of this taxonomy, the analogous difference equation form is also included in this category.

b. Heterogeneous Equations

The traditional heterogeneous Lanchester square equations in their differential equation form can be written as

$$\begin{aligned} dr_j(t)/dt &= \begin{cases} \sum_{i=1}^m k_{ij}b_i(t) & r_j(t) > 0 \\ 0 & r_j(t) = 0 \end{cases} & j = 1, \dots, n, \\ \text{and} \\ db_i(t)/dt &= \begin{cases} -\sum_{j=1}^n k'_{ji}r_j(t) & b_i(t) > 0 \\ 0 & b_i(t) = 0 \end{cases} & i = 1, \dots, m, \end{aligned}$$

where m gives the number of different types of Blue weapons and n gives the number of different types of Red weapons involved in the interaction.

As with the homogeneous case, for the purpose of this taxonomy the analogous heterogeneous Lanchester square equations in their difference equation form are also included in this category.

c. Discussion of Homogeneous Versus Heterogeneous Attrition Equations

As a comparison of the equations just above with those in Section III.B.3 indicates, the distinction between homogeneous and heterogeneous attrition equations (whether they be Lanchester equations or not) is as follows. Since they consider only one type of weapon on each side, homogeneous equations are directly appropriate only if there is essentially only one type of weapon on each side involved in the interaction being simulated. Homogeneous equations can be used if multiple types of weapons are involved, but such use requires: (a) adding together all of the weapons to yield a total number of "notional" weapons on each side, (b) averaging the effectiveness parameters to give a single, overall effectiveness of a Blue notional weapon against a Red notional weapon and vice versa, and then (c) prorating the number of notional weapons killed on each side according to weapon types to yield an estimate of the number of weapons of each type that are killed in the interaction. In contrast, heterogeneous attrition equations inherently account for various types of weapons on each side, they can consider distinct effectiveness parameters for each type of weapon on one side versus each type of weapon on the other side (without always averaging these parameters), and they distinctly compute the number of each type of weapon killed on each side.

Heterogeneous equations can be essentially impossible to solve in tractable closed form. However, they can be solved numerically, and they can easily be used as part of a computerized model.

3. *Traditional Lanchester Linear (Differential and Difference) Equations*

a. Homogeneous Equations

The traditional homogeneous Lanchester linear equations in their differential form can be written as

$$dr(t)/dt = -cb(t)r(t)$$

and

$$db(t)/dt = -c'r(t)b(t) .$$

Again, for the purpose of this taxonomy, the analogous difference equation forms of these equations are also included in this category.

b. Heterogeneous Equations

The traditional heterogeneous Lanchester linear equations in their differential equation form can be written as

$$dr_j(t)/dt = -r_j(t) \sum_{i=1}^m c_{ij}b_i(t) \quad j = 1, \dots, n ,$$

and

$$db_i(t)/dt = -b_i(t) \sum_{j=1}^n c'_{ji}r_j(t) \quad i = 1, \dots, m .$$

Again, for the purpose of this taxonomy, the analogous difference equation forms of these equations are also included in this category.

c. Discussion Concerning Point and Area Fire

It should be noted that no mention was made of point fire or area fire in the discussions above about Lanchester square and linear equations. This can be important because a somewhat commonly held myth is that point fire is somehow inherently related to Lanchester square equations while area fire is inherently related to Lanchester linear equations. In fact, depending on the (perhaps assumed) details of the particular combat being modeled, some types of point fire can be appropriately represented by versions of Lanchester square equations, others by versions of Lanchester linear equations, and still others by other attrition equations, and some types of area fire can be appropriately represented by versions of Lanchester square equations, others by versions of Lanchester linear equations, and still others by other attrition equations. Accordingly, the categorizer of a model here should consider the particular attrition equations being used in the model, not at the rationale (if any) given for the use of those equations.

4. *Attrition Equations in which the Number of Targets Killed Is Structurally Independent of the Number of Shooters*

All of the types of Lanchester equations discussed above have the property that, if the number of shooting weapons is varied, then (except for degenerate cases) the number of targets killed also varies. An attrition process belongs in the category described in this section if this property does not hold and, instead, the number of targets killed remains constant as the number of shooting weapons is varied. The most commonly used attrition process with this property is the one that assumes that a loss rate (or, synonymously, kill rate or attrition rate) applies, where this rate is not structurally dependent on the number of shooters involved. For example, if a model assumes that the loss rate of a particular resource due to enemy fire is given by an input percentage, then that model should be characterized as being one in which the losses of this resource are structurally independent of the number of weapons shooting at it. Other, more complex examples exist in which losses are structurally independent of the number of shooters involved, and all such should be categorized as belonging here .

5. *Other Attrition Equations*

All attrition equations not covered above are classified here as belonging to these "other attrition equation" category. As with Lanchester equations, these other attrition equations can be subdivided into homogeneous equations and heterogeneous equations.

a. Homogeneous Equations

One commonly used type of homogeneous attrition equation is as follows. A scalar measure of the strength (i.e., combat firepower) of the force on, say, side 1 at the start of a given time period is determined by some means (many different methods can be used). Call this measure of strength s_1 . A scalar measure of the strength of side 2, say s_2 , at the start of that time period is also determined. The ratio of these strengths, s_1/s_2 , is calculated (such ratios are frequently called force ratios). Attrition to the strength of each side during the time period is assumed to be some function of this ratio. That is,

$$\Delta s_1 = f_1(s_1/s_2)$$

and

$$\Delta s_2 = f_2(s_1/s_2).$$

(If this homogeneous approach is being used to simulate attrition of heterogeneous forces, then these losses in strength can be prorated over weapon types to determine losses by type.) Since this approach is somewhat common, it can be useful to further subdivide homogeneous attrition equations here into force ratio attrition equations and all other (non-Lanchester non-force ratio) homogeneous attrition equations.

b. Heterogeneous Equations

Heterogeneous attrition equations can be further subdivided into those that are heterogeneous in types of shooters but not types of targets, those that are heterogeneous in types of targets but not types of shooters, and those that are fully heterogeneous in both types of shooters and types of targets. This subdivision technically can be applied to the traditional Lanchester equations presented above, but it is relatively pointless to do so--if heterogeneity is to be considered at all in Lanchester equations then it might as well be fully addressed. However, there exists other attrition structures in which this distinction can be significant. Beyond making this distinction, it may be better to describe the particular attrition equations involved than to make further categorical subdivisions.

6. *Other Types of Attrition Processes*

Attrition in combat models tends to be calculated either using a Monte Carlo method or using some form of attrition equation. In case neither of these two approaches seem like appropriate descriptions of the attrition processes used in some particular model, this "other types of attrition processes" category is included here for completeness.

C. **Summary**

This attrition taxonomy is structured so that each attrition interaction in a model can be characterized as being of exactly one of the types described above. Accordingly, an appropriate descriptive question here concerning a combat model is to give the absolute number and/or the percentage of attrition interactions in the model that belong to each of these types and, if a mix is used, to briefly describe which attrition interactions in the model are simulated using which of these types of attrition techniques.

APPENDIX B

TAXONOMY WORKSHEET

TAXONOMY WORKSHEET

Please use this form to classify models with which you are familiar using the taxonomy described in the text and in Appendix A. Use the *Other Descriptor* spaces for additions to the taxonomy or to list good-to-know information that is useful for a catalogue but not essential for classification. Such data might include systems requirements, run time, size (for storage), data bases, model history, frequency of use, time compression, developer, point of contact, set-up time, pre- or post-processors, security classification, staff operating overhead, principal output parameters, and validity.

A. Model Name: _____

B. Model PURPOSE:

Primary: _____

Other: _____

C. Model QUALITIES:

Span: _____

Domain: _____

Environment: _____

Force Composition: _____

Scope of Conflict: _____

Mission Area: _____

Entities: _____

Processes: _____

D. Model CONSTRUCTION:

Human Participation: _____

Time Processing: _____

Treatment of Randomness: _____

Sidedness: _____

=====

Other Descriptors: _____

APPENDIX C

SIMTAX WORKSHOP ATTENDEES

APPENDIX C

SIMTAX WORKSHOPS ATTENDEES

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George Heinrich
Thomas King
Judith C Krebs
Kenneth E Lavoie
William G Lese
Richard Maruyama
Grant Miller
George Miller
Gary Morton
Dale K Pace
Dean Pappas
Anthony F Quattromani
Thomas M Regan
Vincent P Roske
Dudley Schwartz
C Parks Shaefer
W E Sykes
Matthew J Szczepanek, Jr
Milton G Weiner
Kenneth E Wiersema
Richard I Wiles

SYSCON
IDA
USAF SA
ODUSA (OR)
Boeing
USAF XOIXD
USAMSAA
SYSCON
Data Memory Systems
USA CAA
CIA
BBN Labs
SYSCON
AFHRL
Boeing
AFHRL
USAF SA
USAF CADRE
CENTCOM
TRADOC
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Johns Hopkins/APL
USAF CADRE
SYSCON
Atlantic Analysis
Joint Staff J-8
ANSER
USAF MAC
GAO
USEUCOM
RAND
AMMO
MORS

